LIFE CYCLE COSTS OF ALTERNATIVES FOR F-16 PRINTED CIRCUIT BOARD DIAGNOSIS EQUIPMENT

THESIS

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AFIT/GSS/LAR/94D-3

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Abstract

This study analyzes two alternatives for printed circuit board (PCB) diagnosis for the F-16 depot PCB repair shop from a life cycle cost (LCC) perspective. Alternative 1 assumes the use of the current F-16 automatic test equipment (ATE) while Alternative 2 augments the current ATE with infrared imaging test equipment. Infrared imaging is a developed technology that is currently available to the Air Force in a commercial-off-the-shelf (COTS) form.

Using the Cost Analysis and Strategy Assessment (CASA) Life Cycle Cost (LCC) Model and data from the DL41 database on F-16 PCBs, this study determined that over the current expected life of the F-16, the next twenty-five years, a savings of approximately $1.1 million (1994 dollars) can be realized by augmenting the current F-16 ATE with infrared imaging test equipment. 15% of the F-16 printed circuit boards (PCBs) are single card PCBs which can be tested using infrared imaging test equipment. This study assumes that the total number of PCBs and the percentage of single card PCBs does not change over the F-16's lifetime. Sensitivity analyses are performed varying the percentage of single card PCBs, the total number of PCBs, and the F-16 lifetime to determine the effects these changes might have on the total life cycle cost of implementing Alternative 2.

LIFE CYCLE COSTS OF ALTERNATIVES FOR F-16 PRINTED CIRCUIT BOARD DIAGNOSIS EQUIPMENT

I. Introduction

General Issue

In the Air Force, Air Logistics Centers (ALCs) perform depot level repair on all Air Force weapon systems, including the printed circuit board (PCB). Part of the effort in repairing PCBs involves the use of diagnostic equipment which isolate the failures to the piece part level. Currently, the Air Force uses automatic test equipment (ATE) to test and diagnose the majority of its printed circuit boards (PCBs). Automatic test equipment (ATE) are "... electronic devices capable of automatically or semiautomatically generating and independently furnishing program stimuli, measuring selected parameters of an electronic, mechanical, or electro-mechanical item being tested and making a comparison to accept or reject the measured values in accordance with predetermined limits." (12:3)

Automatic test equipment (ATE) use software called test program sets, written in low level computer languages (usually assembly language) which are printed circuit board (PCB) specific, to run the tests and diagnose the failures. Because each test program set is written in a low level languages with the purpose of testing a specific PCBs, test program sets are very complex and difficult to maintain, increasing the support costs of automatic test equipment (ATE) (21:1). The cost to develop a single test program set ranges from $8,000 to $200,000 depending upon the complexity of the printed circuit board to be tested (3:56; 4:33). Due to the limitations of the test program sets, automatic test equipment (ATE) are accurate only 65 percent of the time in isolating failures and take an average of two hours to isolate failures (21:17). In general, automatic test equipment (ATE) are complex, time consuming to operate, costly, and prone to inaccuracies (23: 41; 25:5).

Photonic techniques (ultrasound, visual, infrared, laser, ultra violet fluorescence, and x-ray) could be used to augment or replace existing automatic test equipment (ATE), resulting in reduced test time and cost (1:I-49; 23:45). Photonics, synonymous with Electro-Optics, is "...the study of the effects of electric fields on optical phenomena." (26:D-41) "Optoelectronic devices are those which convert light into electrical energy or vice versa." (20:1) Much of the photonic technology that has been developed and used by industry for printed circuit board (PCB) testing could benefit the Air Force in its PCB testing. For example, infrared imaging has been used to diagnose failures in PCBs since the mid 1970s (13: 154). Infrared imaging employs the one micron to one millimeter wavelength region of the electromagnetic spectrum to make thermal images of a printed circuit board commonly called a standard thermal profile. The standard thermal profile of a printed circuit board (PCB) being tested is compared with the standard thermal profile of a known good board and/or the standard thermal profile of known faulty boards. Through this comparison, faulty or marginally functional components on the PCB can be detected (23:41; 3:55). By implementing a proven technology, the Air Force could avoid the high costs and risks associated with developing a new technology while replacing aging, time consuming ATE with more efficient test equipment. However, life cycle cost (LCC) analyses must be performed to determine the extent of the potential cost benefit of acquiring and implementing the existing photonic technology for PCB testing and diagnosis at Air Force ALCs. The life cycle cost (LCC) of an item is its total cost at the end of its lifetime. The LCC includes all expenses for research and development, production, modification, transportation, introduction of the item into inventory, new facilities, operation, support, maintenance, disposal, and any other costs of ownership, less any salvage revenue at the end of its lifetime (22:9).

At Ogden Air Logistics Center (ALC), Utah, the Air Force spends approximately $1 billion a year on depot level repair for the F-16 (12:5). Approximately $356 thousand of this is spent each year by the F-16 depot printed circuit board (PCB) repair shop to test and repair PCBs. The F-16 program was developed in the 1970s, and its automatic test equipment (ATE) is becoming antiquated. The F-16 is still in production, and currently there is no new fighter in development to replace the F-16. The last F-16 in production is scheduled to be delivered in March 1997. With its current life span (over twenty-five years), the F-16 will be in the Air Force inventory until the year 2020 (6). Currently, there are no detailed life cycle cost (LCC) estimates for the F-16's depot ATE, and new cost saving technologies have not been investigated to replace or augment the current F-16 ATE.

Infrared imaging is a developed technology available to the Air Force to augment or replace existing automatic test equipment (ATE). Infrared imaging can detect and identify failures and impending failures in printed circuit boards (PCBs) without complex test program sets, and in less time than existing ATE (23: 42). Infrared imaging and fault diagnosis takes from 3 to 20 minutes total to perform versus two hours or more for typical ATE (3:56; 2:1; 27:VI.3). Finally, infrared imaging can be used on most single card PCBs (3:57). Single card printed circuit boards are PCBs consisting of one circuit card with circuits printed on one (single layer) or both (double layers) sides of the circuit card. Of the 372 different F-16 PCBs repaired by the F-16 depot PCB repair shop, 56 (15%) of them are single card PCBs (11).

One initiative to replace automatic test equipment (ATE) in the private industry has been very successful. The Air Force, working with Pratt & Whitney, replaced old and outdated ATE with infrared imaging equipment for the repair of engine power supplies. The results were reduced diagnostic time from three hours to thirty minutes, increased diagnostic accuracy from 65 percent to 90 percent, reduced scrap by 50 percent, and reduced skill level required for technicians to perform fault diagnosis. (12:16-17)

Specific Problem

The purpose of this study is to determine to what extent it is cost effective to augment the current automatic test equipment (ATE) with infrared imaging test equipment for the F-16 repair shop. The F-16 ATE is only 80 percent accurate and takes approximately two hours to diagnose a printed circuit board (PCB), depending on the complexity of the PCB (12:5). Additionally, it takes an average of three test runs to locate all the faults (12:5).

This study will adapt the Cost Analysis and Strategy Assessment (CASA) life cycle cost (LCC) model to estimate the LCCs for two alternatives for F-16 depot printed circuit board (PCB) test equipment: Alternative 1) a baseline LCC for the current F-16's depot automatic test equipment (ATE); and Alternative 2) an LCC for augmenting the existing F-16's depot ATE with infrared imaging test equipment. This study is focused specifically on the F-16 depot PCB repair shop at Ogden ALC, Utah. The LCCs of the baseline and the augmented ATE will be compared. If there is significant LCC savings by augmenting the F-16 ATE with infrared imaging test equipment, Ogden ALC will be able to use the results of this study to aid them in gaining funding support to augment their current F-16 ATE with infrared imaging test equipment. Such funding support would most likely come from the Productivity, Reliability, Availability and Maintainability (PRAM) program office at Wright-Patterson AFB.

> The Productivity, Reliability, Availability and Maintainability (PRAM) program was formed in 1975 by the Air Force Chief of Staff to reduce current and potential operation and support (O&S) costs and to improve the effectiveness of Air Force operational systems, subsystems, and equipment. This unique organization is made up of engineers, logisticians, and managers experienced in the complete life cycle of weapon systems. PRAM authorizes "front end" investments in prototyping projects leading to improved operational and combat readiness, reduced operating and support costs of in-service weapon systems and equipment, increased

> efficiency in maintenance procedures, improved productivity, improved standards and specifications for developing, procuring, and testing systems, and adaptation of existing equipment to broader applications. (18)

Finally, the LCC comparison process used in this study may be applicable for other Air Logistics Centers to assess potential cost benefits of replacing or augmenting their ATE with infrared imaging test equipment.

Overview of Thesis

This thesis adapts the CASA LCC model to estimate life cycle costs for the F-16 depot printed circuit board (PCB) repair shop. The LCC model predicts the LCC for the current F-16 automatic test equipment (ATE) over the next twenty-five years (Alternative 1), and the LCC of augmenting the F-16 ATE with infrared imaging test equipment for the next twenty-five years (Alternative 2). Any potential life cycle costs savings by augmenting the current F-16 ATE with infrared imaging test equipment (Alternative 2) should be revealed by this study.

This thesis has three additional chapters. The second chapter provides a detailed background of automatic test equipment (ATE), infrared imaging test equipment, and life cycle cost analysis. Chapter three outlines the methodology used in collecting and analyzing the research data, and contains the research findings and data analysis. Chapter four summarizes the major conclusions and presents recommendations for future research.

II. Literature Review

Overview

With decreasing defense budgets, a leaner Air Force, and the move toward making processes more cost efficient, it makes sense to scrutinize current Air Force practices to determine if there are methods to improve the processes the Air Force uses to performs its mission. In particular, the area of printed circuit board (PCB) testing, diagnosis, and fault isolation requires closer inspection. Replacing or augmenting current Air Force automatic test equipment (ATE) with infrared imaging test equipment may be a cost effective alternative for PCB testing, diagnosis, and fault isolation. This chapter will present the findings of the literature review of current ATE technology, infrared imaging technology used in PCB testing, and life cycle costing.

Air Force Air Logistics Centers use ATE to test, diagnose, and fault isolate PCBs for a variety of weapons systems in the Air Force inventory. In the Air Force maintenance system, faulty PCBs in line replaceable units (LRUs) are identified by LRU testing performed at the field level operational maintenance unit. The faulty PCBs which are considered shop replaceable units (SRUs) are removed from the line replaceable unit at the field organization and replaced with good PCBs from the spares stock. The faulty PCBs are then sent to an Air Logistics Center where a depot level maintenance unit tests and repairs the PCBs and puts them back into the spares stock.

With regard to the F-16 weapon system, there are 372 different kinds of printed circuit boards (PCBs) that are repaired by the F-16 depot PCB repair shop at Ogden Air Logistics Center. These PCBs are at the heart of the different avionics found on the F-16 which include navigation systems, weapons targeting systems, flight instrument systems, and flight control systems, to name a few. Any system on the F-16 requiring any kind of avionics will have PCBs associated with the avionics line replaceable units that are part of that system.

ATE Process Overview

One approach for testing and diagnosing printed circuit boards (PCBs) is through manual probing which uses software resident within the automatic test equipment (ATE) to guide a technician through a series of steps to probe circuit paths and measure the output (23:41). The PCB is connected to the ATE and powered through its connectors. The ATE steps through a fault tree for a given PCB and directs the technician to test the different circuit paths and nodes until the fault is isolated. When a fault is detected at an output pin, the technician is directed to track back node by node with the probe until the node is found where inputs are all good and the output is bad, isolating the faulty component (4:9). The technician then replaces the faulty component.

Another approach which is slightly more automated and requires less interaction with the technician uses a test fixture consisting of a large number of probes to gain access to the internal nodes on a PCB (23:41). The "bed of nails" fixture approach is similar to the first approach except that a test program set (TPS) determines and isolates the fault by analyzing the various measurements from each of the probes on the test fixture. This second approach makes use of a fault dictionary which consists of a list of possible failures that can be detected at the PCB output pins for each input of the test diagnostic sequence exercised by the test program set (4:8). At the completion of the test program set, a prioritized list of probable causes of the fault(s) known as ambiguity groups are reported to the technician (23:41). This list may possibly contain only one cause of the fault in which case the technician knows exactly what component on the PCB must be replaced. If there is more than one cause listed, the technician may replace all the components listed, or replace stepwise each component, re-testing the PCB on the ATE after each replacement until the PCB tests satisfactorily at which time it is considered repaired and is returned to the spares stock.

Positive Aspects of ATE

One advantage of automatic test equipment (ATE) is that the technician operating the equipment does not need to be highly skilled in electronic circuit debugging. In the case of a manual probe, the ATE guides the technician as to which circuit paths to probe and test. In the case where test program sets are used, the test program set performs all the testing, providing the technician with an ambiguity group at the end of testing. In both cases, the ATE is making the decisions.

According to Clark, Georgi and Van Weerthuizen, manual probing tends to be more accurate than using test program sets and fault dictionaries in locating defective devices as well as dealing with multiple failures. On the other hand, test programs sets and fault dictionaries require a less skilled technician and take less time for fault diagnosis than manual probing (4:9).

Negative Aspects of ATE

One negative aspect of automatic test equipment (ATE) is that the fault dictionaries often return large ambiguity groups and cannot detect multiple failures in a circuit path (23:41; 4:9). Another draw back of ATE is that misprobing of printed circuit boards (PCBs) can occur due to an error by the technician or due to the conformal coating on the PCBs (23:41). The conformal coating on PCBs helps protect the PCB from the environment and from accidental contact with other electrical devices which might damage the PCB. Using probes to test a PCB can cause damage to the conformal coating and electronic components on PCBs which consequently must be replaced (23:41; C1:56).

The literature does not indicate with what frequency damage occurs to a PCB due to probing or what the damage typically costs.

Another negative aspect is that ATE are not able to diagnose intermittent failures or detect components on a PCB that are on the brink of failing (23:41,42). As a result, many PCBs with intermittent failures or which have components due to fail soon are often put back into the spares stock as having re-tested OK (RETOK). Another disadvantage of ATE is that they require long test times (23:41; 25:5), on the order of 2 hours or more (2:2; C1:56) because of the complexity of PCBs and the corresponding complexity of the test programs sets to test the PCBs. Due to the complexity of PCBs, and the number of unique circuit paths a test program sets must test to detect a fault, not every path is covered, resulting in a 95% detection rate on average for test program sets (C1:55). For a test program set to detect the other 5% of faults, the cost of the test program set would be beyond the benefit gained by the extra capability (C1:55). A major disadvantage of ATE is that they are designed for specific types of PCBs which results in a large number of ATE required to test all of a weapon system's PCBs.

Infrared Imaging Test Equipment Process

Infrared imaging techniques are based upon the principle that each component of an energized printed circuit board (PCB) emits infrared electromagnetic radiation or heat (17:28; 10:2; 5:9; 24:289; 23:42). With infrared imaging test equipment, the suspect PCB is provided power through its connectors (10:4). The infrared image or standard temperature profile of the PCB (27:IV.2; C1:55) is recorded and compared with the standard temperature profile of a known fault free PCB or a database of reference scans of infrared images of PCBs with known faults (10:4 ; 17:28). The comparison and subsequent fault detection and diagnosis can be performed either by a highly skilled technician (27:VI.1-VI.2), engineer (17:29), computer program (27:IV.2; 9:9-12) or more recently by an artificial neural network (ANN) (23:42; 2:1) which identifies the faulty component(s).

According to a Productivity, Reliability, Availability and Maintainability (PRAM) program final report on a neural radiant energy detection system, Ogden Air Logistics Center (ALC) uses an infrared imaging system with an artificial neural network as the sole system to diagnose and fault isolate printed circuit boards (PCBs) for the Advance Combat Maneuvering Instrumentation (ACMI) system. The Advance Combat Maneuvering Instrumentation was developed for the A-9 missile. Any airplane, including the F-16, that can be equipped with the A-9 missile will have the Advance Combat Maneuvering Instrumentation. By using the infrared imaging system for ACMI PCBs, Ogden ALC estimates they will realize a savings of over $5 million over the useful life of the ACMI system (2:2).

According to Mr. Mike Radecki, an electrical engineer at the Aerospace Guidance and Metrology Center (AGMC), the same kind of infrared imaging test equipment with the artificial neural network used by Ogden ALC was used experimentally by AGMC to test PCBs in the Minuteman ICBM computer. The purpose of the experiment was to determine if the infrared imaging test equipment could help AGMC detect impending failures in the Minuteman PCBs. AGMC's experience with the infrared imaging test equipment was not as positive as Ogden ALC's. The PCBs that were tested were eight layer boards, so only the two outer layers could by imaged using the infrared imaging test equipment. Additionally, the components on the PCBs were mounted very close together, making it difficult at times to distinguish the separate infrared signature of each of the components. Mr. Radecki stated that the infrared imaging test equipment is best utilized on single card PCBs with well spaced components rather than multi-layer PCBs with tightly spaced components (19).

Positive Aspects of Infrared Imaging Test Equipment

Infrared imaging and fault diagnosis takes as little as three to twenty minutes to run (C1:56; 2:1; 27:VI.3). Damage caused by probing cannot occur, because infrared imaging test equipment makes no physical contact with the printed circuit board (PCB) except through the board's outer electrical connections which are used to energize the PCB (10:2; C1:56). Infrared imaging is not dependent upon probing all possible circuit paths which can alter electrical loading effects, but is able to check out the entire PCB for faults including connectors, wiring paths, and conformal coating (10:2). Another advantage of infrared imaging test equipment is that it can detect intermittent and impending failures of components on a PCB, increasing the PCB's reliability (23:42; 2:11,12). In other words, the reliability of a group of PCBs, for example PCBs in a spares stock, actually increase because PCBs with intermittent or impending failures are detected with the infrared imaging test equipment, and are not allowed to go back into the spares stock until they are repaired. Because the infrared standard thermal profile is the only parameter measured (10:2), complicated and expensive test program sets are not required to probe and test all the different circuit paths (C1:56). Perhaps the biggest advantage in using infrared imaging test equipment is its versatility in being able to test a variety of different PCBs (24:7).

Negative Aspects of Infrared Imaging Test Equipment

A notable drawback of using infrared imaging test equipment is the requirement for highly skilled technicians or engineers to perform the fault detection and isolation in the absence of a computer program or artificial neural network to perform these functions (27:IV.1-IV.2; 17:29). This drawback appears to be more of a problem of the past when the technique was limited by the enormous storage space and computer time required to archive thermal images on mass media. Consequently, technicians skilled in interpreting infrared images were required in operating the test equipment and diagnosing the printed circuit board (PCB) faults. Recent advancements in image compression techniques, large mass storage devices, and artificial neural networks have effectively eliminated these limitations (2:5).

The main limitation of infrared imaging test equipment is that it can only make infrared images of the outermost layers of a PCB. A PCB composed of several circuit cards stacked together with circuits printed on both sides of each card would not be a suitable candidate for testing and fault isolation by solely using infrared imagining test equipment (19). However, PCBs consisting of a single circuit card with circuits printed on one or both sides are good candidates for testing by infrared imaging test equipment. Of the 372 different PCBs tested and repaired by the F-16 depot PCB repair shop, 56 (15%) could be tested using infrared imaging test equipment.

A significant amount of work has been published on ATE and to a more limited extent on infrared imaging test equipment. In most of these published works, the advantages and disadvantages of ATE and/or infrared imaging test equipment are presented. Most of these articles agree that infrared imaging test equipment will perform as well as ATE, and the unique aspects such as speed in testing, versatility in testing different PCBs and detection of intermittent or impending failures give infrared imaging test equipment some clear advantages (C1, 13, 17, 23, 24). Additionally, most authors predict that savings can be realized by using infrared imaging test equipment to test PCBs. There is, however, a lack of any life cycle cost (LCC) studies to estimate the LCC savings of replacing or augmenting ATE with infrared imaging test equipment. Because of this lack of LCC studies, this thesis attempts to provide LCC information on augmenting the F-16 ATE with infrared imaging test equipment.

Life Cycle Costs

Life cycle costs (LCCs) are the complete cost of an item in four categories: research and development (R&D), production, operation and support (O&S), and disposal. These costs include "... all expenses for research and development, investment, modification, transportation, introduction of the item into inventory, new facilities, operation, support, maintenance, disposal, and any other cost of ownership, less any salvage revenue ..." (22:9). The main cost categories and the way these costs are characteristically incurred over time are depicted in Figure 2-1.

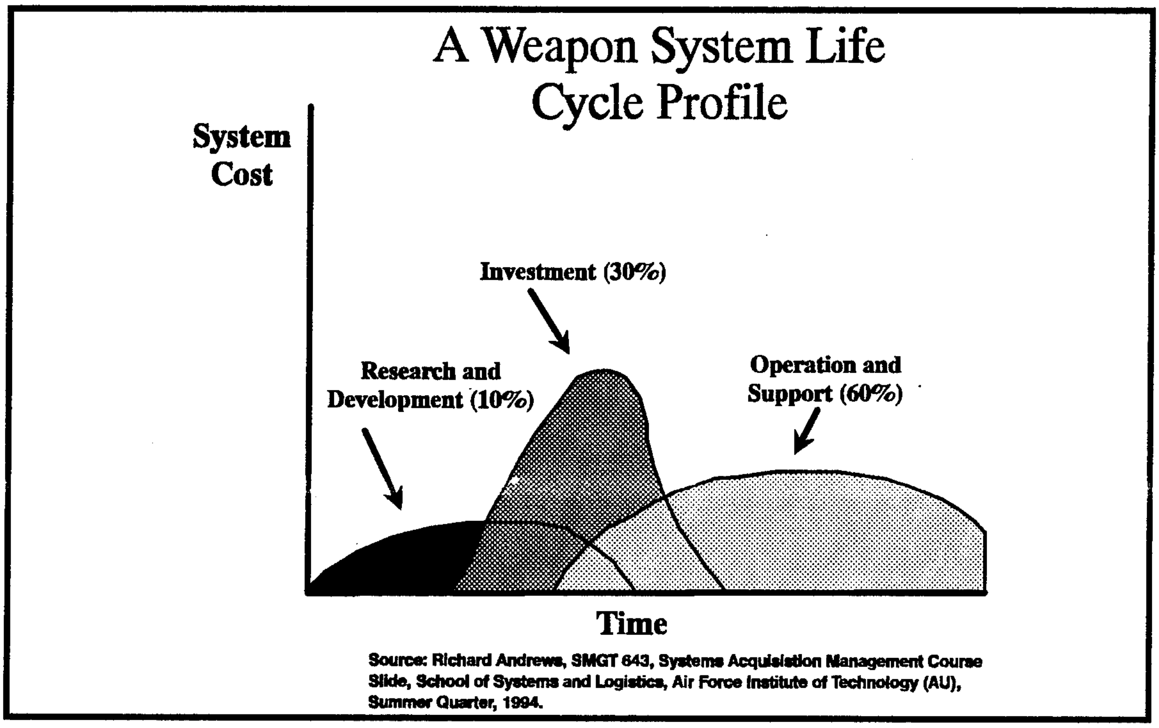

Figure 2-1. Life Cycle Costs Over Time

Life cycle cost (LCC) analysis has six primary uses: long range planning and budgeting, comparison of competing programs, comparison of logistics concepts, decisions about the replacement of aging equipment, control over an ongoing program, and selection among competing contractors (22:11-12). This study focuses on using the

LCC analysis and cost comparison to provide the necessary information for making a decision about augmenting the current F-16 automatic test equipment (ATE) with infrared imaging test equipment. It is important to note, that for a life cycle cost comparison to be valid, the benefits of the alternatives being compared must be equal; if the benefits are not equal, then the LCC and benefits of each alternative must be considered in making a decision (7:1). Naturally, one would choose an alternative which provides greater benefits at a lower cost over a second alternative which provides lessor benefits at a higher cost. The other case, where one alternative has a higher cost and greater benefits, and the second alternative has a lower cost and lessor benefits, is more difficult to determine. Such a case would require other information in addition to the LCC and benefits to make a good decision.

Operation and Support (O&S) Costs

O&S costs include training, personnel, support equipment, maintenance, facilities, transportation, provisioning, and any other cost incurred during the deployment life of the item. O&S costs usually occur over a ten to twenty year period, and generally compose the largest part of the life cycle cost (LCC) (22:67). More importantly, as systems (such as the B-52 bomber) are used longer than their original projected lifetimes, O&S costs become an even larger proportion of the total LCC. Other cost drivers which impact O&S costs are the reliability and maintainability (R&M) of the item. In other words, how often the item breaks (mean time between failure (MTBF)) and how long it takes to repair the item (mean time to repair (MTTR)) have a significant effect on the O&S costs. Consequently, new technologies, materials, and processes which can improve the R&M of a system will potentially reduce the O&S costs of the system over its lifetime, reducing the overall LCC.

Program Costs Over Time

Two important factors which must be considered when performing an LCC analysis are the time value of money and inflation. Future dollars must be discounted to account for the time value of money. A dollar today is not equal to a dollar tomorrow even in a economy without inflation because of interest (7:41). To account for the time value of money (the present value of the present value of future dollars), a discount rate must be applied. This study uses constant dollars relative to the purchasing power of the dollar in 1994. Currently, the DOD uses an inflation adjusted real rate of 7% in determining the present value of future dollar expressed in units of constant purchasing power (15).

Cost Analysis and Strategy Assessment (CASA) LCC Model

The CASA model has been used by the Air Force in predicting depot support activities (7:77). The CASA model was chosen for this effort because of its usefulness in predicting costs during the operation and support (O&S) phase of the life cycle cost (LCC) when key development and design features are known. The CASA model uses a mix of accounting and simulation techniques to predict O&S costs. The CASA model was developed by Honeywell for the Defense Systems Management College (DSMC) in 1986 (7:77). Version 3.0, which is used in this study, was released in 1993 by DSMC, and is more user friendly than earlier versions. The CASA model can run on a personal computer.

LCC Assumptions and Ground Rules

This study is based on the F-16 depot printed circuit board (PCB) repair shop at Ogden Air Logistics Center, Hill AFB, Utah which currently uses automatic test equipment (ATE) as the sole means to test and repair PCBs. The infrared imaging test equipment is assumed to be commercial-off-the-shelf (COTS) and requires no engineering development for use by the F-16 depot PCB repair shop. Thus, all research and development costs are complete and will not contribute to the current life cycle cost (LCC) for ATE and infrared imaging test equipment. Initial set-up and training costs for using the infrared imaging test equipment is included in the procurement cost of the equipment. Additionally, this study assumes the residual value and disposal costs of the ATE and infrared imaging test equipment are negligible for comparison purposes. Therefore, the LCC analysis only includes the operation and support (O&S) costs for the ATE and the procurement and O&S costs for the infrared imaging test equipment.

III. Research Findings and Results

Overview

This chapter focuses on the findings of the research and the results of the cost estimating efforts using the Cost Analysis and Strategy Assessment (CASA) life cycle cost (LCC) model. In order to determine if there is a cost savings in augmenting current automatic test equipment (ATE) with infrared imaging test equipment (Alternative 2), the baseline LCC of the current ATE only, Alternative 1, must be determined and compared to Alternative 2. Finally, the LCC of Alternative 1 and Alternative 2, as predicted by the CASA model, are analyzed with regard to sensitivity analysis of potential future changes.

Data Collection

Cost data were collected from the DL41 data base at Ogden ALC to determine the actual yearly operation and support (O&S) costs for the F-16 ATE. Other data were also collected from the F-16 depot to be used in the life cycle cost (LCC) model to project future O&S costs. Cost data were also collected from South-West Research, a contractor with previous infrared imaging test equipment activation experience at Ogden Air Logistics Center (ALC), to determine acquisition costs for the infrared imaging test equipment. Additionally, cost data were collected from the DL41 data base for the Advance Combat Maneuvering Instrumentation repair shop at Ogden ALC to determine the current O&S costs of the infrared imaging test equipment.

Due to Ogden ALC personnel and time limitations, all of the cost data for the 372 different F-16 printed circuit boards (PCBs) repaired by Ogden ALC could not be obtained for Alternative 1 (fault isolation by ATE only). A random sample of 66 PCBs were obtained from the DL41 cost data base at Ogden ALC. In the sample, at least one PCB was taken from every line replaceable unit. The cost data were analyzed revealing a mean cost of repair of $951.26 per PCB. For a 95% confidence interval, the range of the interval was $880.72 to $1011.33 per PCB.

The sample for the infrared imaging test equipment were taken from the Advance Combat Maneuvering Instrumentation repair shop at Ogden ALC. The sample was from an unknown population size. Thirty PCB samples were obtained from the DL41 cost data base. The cost data was analyzed revealing a mean cost of repair using infrared imaging test equipment of $153.80 per PCB. For a 95% confidence interval, the range of the interval was $146.42 to $161.13 per PCB.

The major cost driver for fault isolation with ATE is manpower. The average PCB fault isolation, repair, and verification process for F-16 PCBs takes approximately eleven hours which includes an average PCB fault isolation and repair process of nine hours for ATE (8). The fault isolation and repair process involves two hours for ATE fault isolation, and one hour for repair of the PCB. Due to the inaccuracies of the ATE, the fault isolation and repair process (three hour duration) is repeated an average of three times until the PCB is repaired. Finally, another two hours on the ATE is required to verify the PCB was repaired.

The infrared imaging test equipment can fault isolate PCBs in minutes and are very accurate at isolating faults. The repair process involves 25 minutes to fault isolate with infrared imaging test equipment, one hour for repair of the PCB, and another 25 minutes to verify the PCB was repaired. With infrared imaging test equipment, the average PCB fault isolation and repair process can be reduced from nine hours (using ATE) to about fifty minutes, and the average PCB fault isolation, repair and verification process time can be reduced from eleven hours (using ATE) to one hour and fifty minutes (3:56; 2:1,2). This study assumes the F-16 PCBs are similar to the Advance Combat Maneuvering Instrumentation PCBs. The average fault isolation, repair, and verification process described above has a 6 to 1 ratio of the time to fault isolate, repair, and verify a PCB using ATE to the time to fault isolate, repair, and verify a PCB using infrared imaging test equipment. This fault isolation, repair, and verification process data was cross-checked with the cost data. The DL41 cost data gave a 6.6 to 1 ratio of cost to fault isolate, repair and verify a PCB using ATE to the cost to fault isolate, repair, and verify a PCB using infrared imaging test equipment.

CASA Model Operation

This study uses the current operation and support (O&S) costs of the F-16 depot printed circuit board (PCB) repair shop which were entered in the Cost Analysis and Strategy Assessment (CASA)model. The CASA model was used to estimate the life cycle cost (LCC) of using the current ATE (Alternative 1) over the next twenty-five years which is the current Air Force projection of depot support required for the F-16 (6). For the CASA model to be adapted for this study (depot repair of PCBs, which is a very small subset of the total LCC), many inputs had to be omitted. An example of this omission, would be in the levels of repair. The CASA model allows for three levels of maintenance (organic, intermediate, and depot). Since this study is looking at depot repair costs, the organic and intermediate levels of maintenance were omitted in the CASA model.

A problem with the cost data provided by Ogden Air Logistics Center was that the cost data was a summation the total cost of repair for each PCB. A rough break-out of the major cost drivers were obtained through interviews with the cost data personnel. The DL41 cost data was broken up into the following categories for the CASA model: operation labor (fault isolation and verification time), repair labor (repair of the PCBs), technical data revisions (update of technical orders), item management (planning and control of the PCBs), training, and miscellaneous O&S (additional fault isolation time) (14).

For Alternative 1, operational and O&S labor, key inputs to the CASA model were average operating hours per month (160), depot labor rate ($9.61), maintenance action cost factor (430), maintenance cost factor level (1), and cost adjustment factor (1). For repair labor, key inputs were portion of time spent on re-test OK (RETOK) (.75), consumable cost factor (.1), earned hour ratio (1), spares confidence level (95), support equipment utilization factor (1), operation hours cost factor (120), and total quantity of parts required (373). For technical data revisions, the key inputs were cost per page ($50) and number of pages updated (20). For Training, the key inputs were hours per course (40) and the turnover rate (.1). For Alternative 2, average operating hours per month (120), maintenance action cost factor (300), re-test OK (.5), and operation hours (90) were the key inputs that were modified. Tables 4-1 and 4-2 contain the CASA model output for Alternative 1 and Alternative 2 respectively.

Model Output

Table 3-1. CASA Model Output for Alternative 1

Year	Operational Labor	Repair Labor	Recurring Training	Tech Data Revision	Recurring Item Management
1994	306.6	44.4	.1	1	3.8
1995	295.2	42.7	.1	1	3.6
1996	295.2	42.7	.1	1	3.6
1997	295.2	42.7	.1	1	3.6
1998	295.2	42.7	.1	1	3.6
1999	295.2	42.7	.1	1	3.6
2000	297.9	43.1	.1	1	3.7
2001	300.6	43.5	.1	1	3.7

Table 3-1 continued. CASA Model Output for Alternative 1

Year	Operational Labor	Repair Labor	Recurring Training	Tech Data Revision	Recurring Item Management
2002	313..4	43.9	.1	1	3.8
2003	306.3	44.4	.1	1	3.8
2004	300.5	43.5	.1	1	3.7
2005	294.9	42.7	.1	1	3.6
2006	289.5	41.9	.1	.9	3.6
2007	284	41.1	.1	.9	3.5
2008	278.7	40.4	.1	.9	3.4
2009	273.5	39.6	.1	.9	3.4
2010	268.4	38.9	.1	.9	3.3
2011	263.4	38.1	.1	.9	3.3
2012	258.4	37.4	.1	.8	3.2
2013	253.6	36.7	.1	.8	3.1
2014	248.9	36	.1	.8	3.1
2015	244.2	35.4	.1	.8	3
2016	239.7	34.7	.1	.8	3
2017	232.5	34.1	.1	.8	2.9
2018	230.8	33.4	.1	.8	2.9
2019	226.5	32.8	.1	.7	2.8

Table 3-2. CASA Model Output for Alternative 2

Year	Operational Labor	Repair Labor	Recurring Training	Tech Data Revision	Recurring Item Management
1994	265	41.6	.1	1	3.8
1995	250.9	41.4	.1	1	3.6
1996	250.9	41.4	.1	1	3.6
1997	250.9	41.4	.1	1	3.6
1998	248.2	41.3	.1	1	3.6
1999	251.9	41.4	.1	1	3.6
2000	253.6	41.4	.1	1	3.7
2001	255.2	41.5	.1	1	3.7
2002	258.9	41.6	.1	1	3.8
2003	261.7	41.6	.1	1	3.8
2004	255.1	41.5	.1	1	3.7
2005	250	41.4	.1	1	3.6
2006	245.3	41.2	.1	.9	3.6
2007	242.1	39.1	.1	.9	3.5
2008	234	38.3	.1	.9	3.4
2009	228.9	37.5	.1	.9	3.4
2010	223.7	36.8	.1	.9	3.3
2011	219.1	35.9	.1	.9	3.3
2012	215.1	35	.1	.8	3.2
2013	210.5	34.2	.1	.8	3.1
2014	206.2	33.4	.1	.8	3.1
2015	202.7	32.6	.1	.8	3

Table 3-2 continued. CASA Model Output for Alternative 2

Year	Operational Labor	Repair Labor	Recurring Training	Tech Data Revision	Recurring Item Management
2016	199.1	31.7	.1	.8	3
2017	195.8	30.8	.1	.8	2.9
2018	192.3	29.9	.1	.8	2.9
2019	198.6	29	.1	.7	2.8

Assumptions for the LCCs and CASA Model

1. The PCBs from the F-16 and ACMI programs are similar in complexity.
2. The single card PCBs are similar to the multi-layer PCBs repaired in the F-16 repair shop.
3. The labor costs to operate infrared imaging equipment are equal to the labor costs to operate the ATE.
4. The benefits of Alternative 1 and Alternative 2 are equal.
5. Disposal costs of Alternative 1 and Alternative 2 are equal.
6. All PCBs repair costs are captured in the DL41 data base.
7. The CASA model can accurately predict Alternative 1 and Alternative 2 complete LCC.

Impacts of the Assumptions

The above assumptions were necessary due to the cost data and CASA model limitations. Assumption number one was necessary, because the there was no method available to distinguish between a multi-layer PCB and a single-layer PCB. The PCBs are tracked by national stock number by the repair shop and the DL41 cost data base. Inside on the national stock number, there were no codes to identify the type of PCB. It would have been nice to know which of the PCBs were multi-layer and single-layer, because it is likely there is a difference in cost of repair. The multi-layer PCBs are more likely to have a higher repair cost. If this study could have distinguished between a multi-layer PCB and single-layer PCB, it would have increased the accuracy of Alternative 2. Likewise, assumption number two assumed a similarity between the PCBs of the ACMI and F-16 weapon system. It is likely that the repair costs of the F-16 (85% multi-layer) are higher than the ACMI repair costs (100% single-layer) even if the PCBs were repaired with ATE.

Assumption number three is fairly accurate. With the neural network, the level of technician labor grade of operating infrared imaging equipment is very similar to the labor grade required to operate the ATE. Assumption number four assumes the benefits of Alternatives 1 and Alternative 2 are similar. It is likely the benefits of Alternative 2 are better than the benefits of alternative 1, but we were unable to quantify the difference. In Alternative 2, using the infrared imaging test equipment is likely to increase the reliability of the PCBs, increase the availability of the PCBs, reduced scrap, reduce maintenance costs on ATE test program sets, and reduce the spares cost due to a lower number of spare PCBs required at the depot.

Assumption number five assumes the disposal costs are equal. Again, we were unable to quantify the costs. While the ATE is PCB unique, the infrared imaging test equipment can be used on other weapon systems. The ATE is older and has a higher support cost as its spares become obsolete. Also, the disposal costs may be higher due to new environmental restrictions since the ATE was built during the 1970s.

Assumption number six assumes all PCB repair costs are captured in the DL41 data base. There are support organization costs which are not included in the data base. An example would be the calibration cost of the ATE. The ATE has to be calibrated periodically by a support organization. With infrared imaging test equipment operating, there would be a decrease in the use of the ATE which may lower the periodic calibration cost. Assumption number seven assumes the algorithms in the CASA model can accurately predict the LCC of Alternative 1 and Alternative 2.

LCC Comparison and Sensitivity Analysis

Using the average cost of $951.26 per printed circuit board (PCB) for the 372 different types of PCBs, the annual budget of the repair shop for 1994 was estimated to be $354 thousand. Using inflation and discount rates, the Cost Analysis and Strategy Assessment (CASA) model predicted a total life cycle cost (LCC) of $9.253 million (1994 dollars) for Alternative 1. The overall results of running the CASA model for Alternative 1 and Alternative 2 can be found in Appendix A.

Using an average cost of $153.80 per PCB for 15% of the 372 PCBs and $951.26 per PCB for the remaining 85% of the 372 PCBs, the annual budget of the repair shop augmented with infrared imaging test equipment for 1994 was estimated to be $309 thousand. Using inflation and nominal discount rates, the CASA model predicted a total LCC of $8.147 million (1994 dollars) for Alternative 2. Over a twenty-five year period, maintaining the current mix of the 372 PCBs that can be tested using infrared imaging test equipment (15%) and those that must be tested using current ATE (85%), the potential LCC savings by implementing Alternative 2 is slightly more than $1 million (1994 dollars).

Figure 3-1 shows the cumulative LCC per year of Alternative 1 and Alternative 2. Initially, the plot of Alternative 1 is below Alternative 2 which is due to the acquisition cost of the infrared imaging test equipment ($128, 000) in Alternative 2. As the number of years increase to 25, Alternative 2 ends up with a lower LCC by $1.1 million. Given that the current mix of PCBs, the total number of PCBs, and the average number of PCBs repaired each year remains constant, Alternative 2 will hit its break-even point (recover the cost of acquiring the infrared imaging test equipment) in three years. The break-even point is where the cumulative LCCs of Alternative 1 and Alternative 2 intersect.

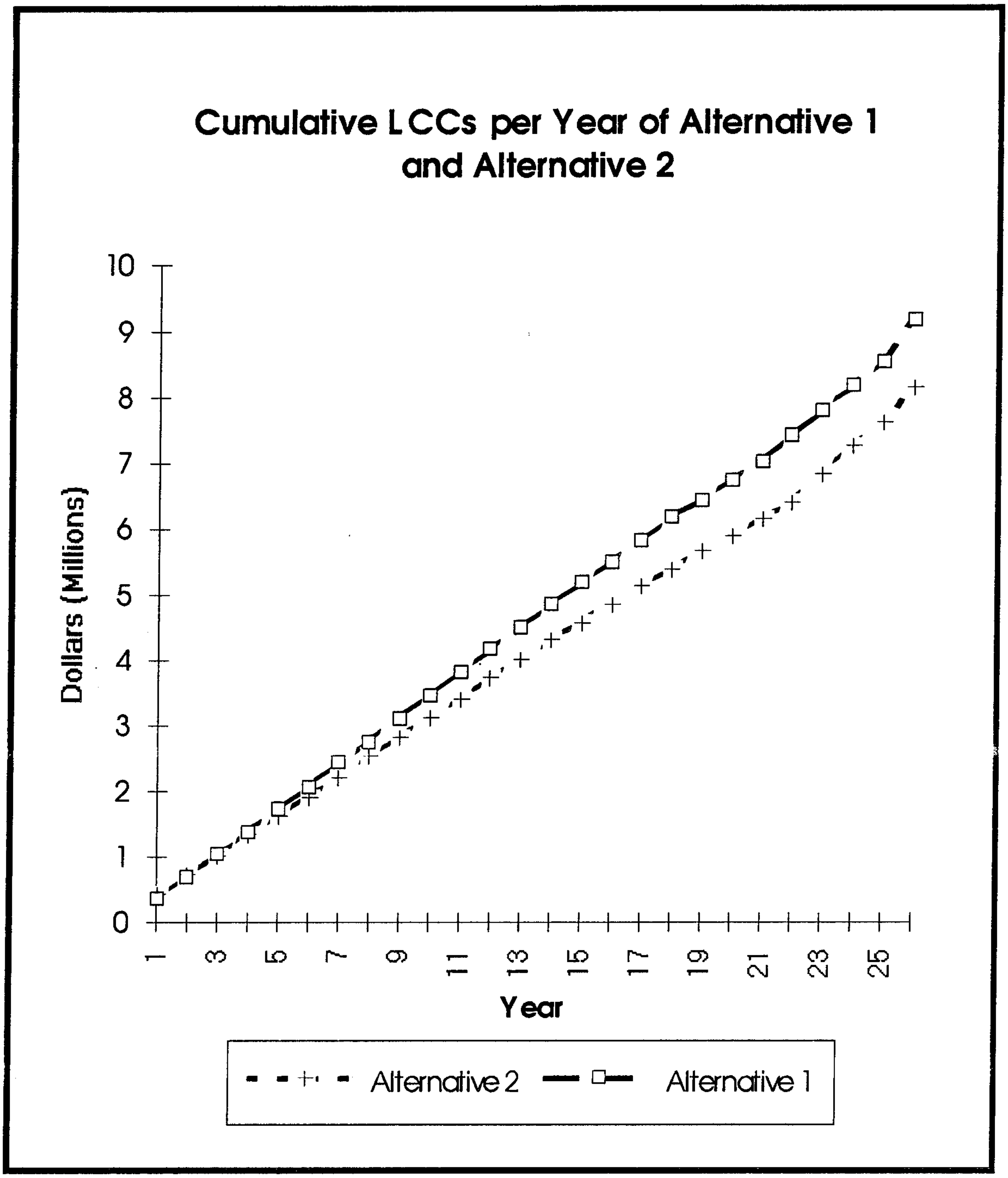

Figure 3-1. Cumulative LCCs per Year of Alternative 1 and Alternative 2

Figure 3-2 shows the LCC of augmenting the F-16 ATE with infrared imaging test equipment (Alternative 2) assuming different percentages of single card PCBs (those which can be tested using the infrared imaging test equipment). Figure 4-2 assumes the number of different types of F-16 PCBs repaired at Ogden ALC remains constant at 372. Even at small percentages of single-layer PCBs (5%), a savings of $485 thousand can be achieved with alternative 2. If the percentages of single-layer PCBs increases to 40%, a LCC saving over three million dollars can be achieved. These large savings are due to the long life (25 years) of the F-16 operation and depot support required. At 15%, the current mix of single-layer circuit cards at the F-16 PCB repair shop, a $1.1 million dollar savings can be achieved.

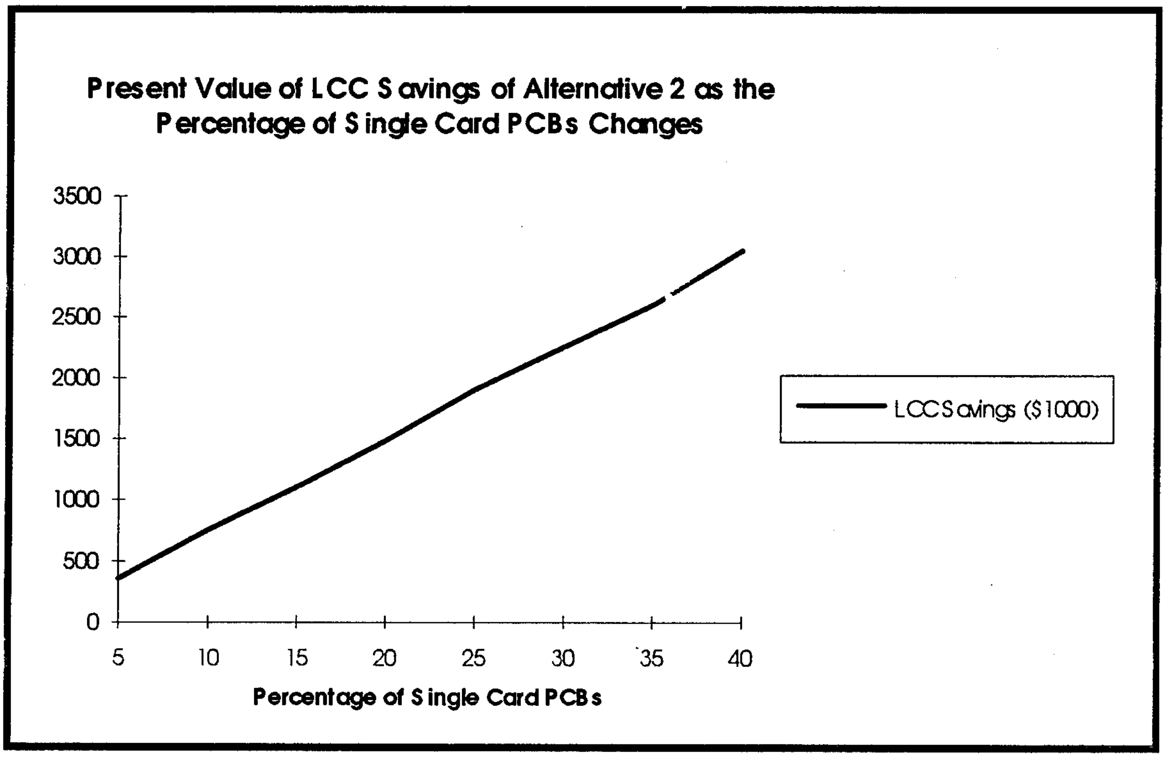

Figure 3-2. Present Value of LCC Savings of Alternative 2 as the Percentage of Single Card PCBs Changes

Figure 3-3 shows the LCC savings of Alternative 2 as the cost ratio of ATE repair costs to infrared imaging test equipment PCB repair costs varies. A cost ratio of one means the cost of repair using ATE augmented with infrared imaging test equipment (Alternative 2) is \$951 (the current cost of repair for ATE, Alternative 1) and there is no LCC savings for Alternative 2. As the repair cost ratio changes from four to eight, the LCC savings varied less than \$100 thousand which demonstrates a greater confidence in the LCC savings for Alternative 2. The cost data sampled in this study had a 6.6 to 1 repair cost ratio. Using a 95% confidence interval for the ATE and infrared imaging test equipment cost data sampled from the DL41 data base, the worst case ratio is 5.5 to 1, and the best case ratio is 6.9 to 1. Given the 95% confidence interval, the LCC savings of one million dollars by Alternative 2 is a reasonable estimate.

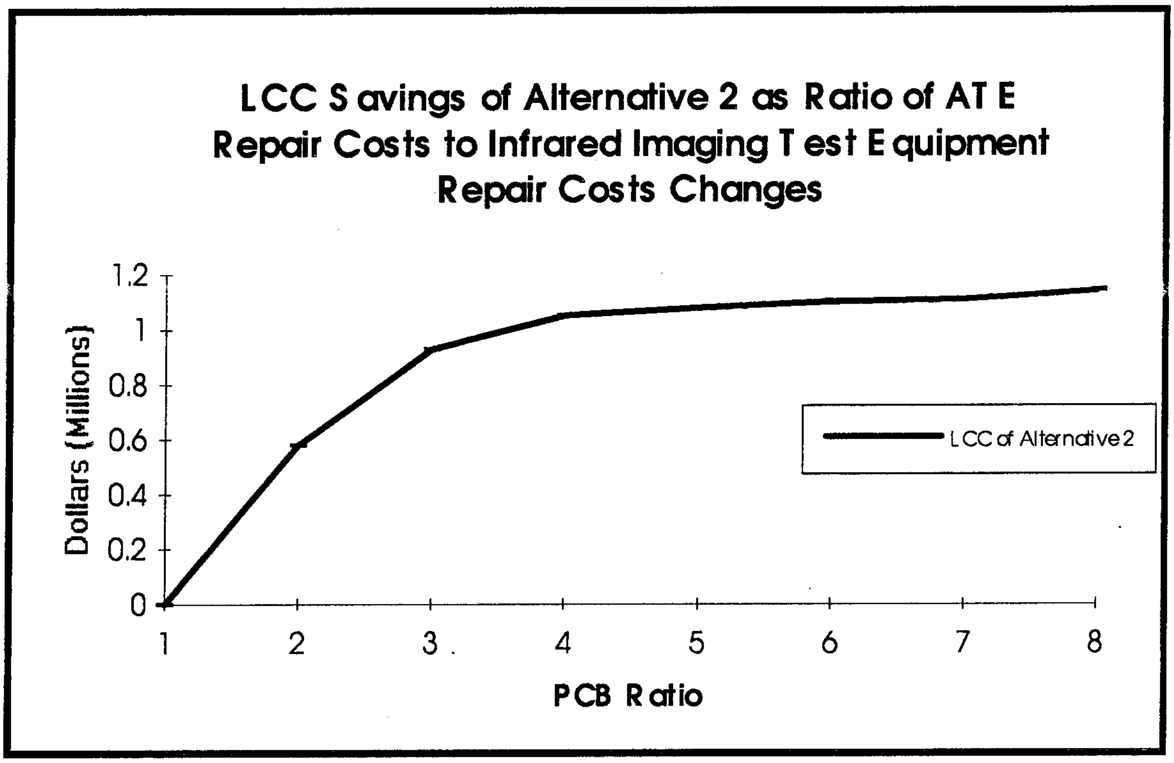

Figure 3-3. LCC of Alternative 2 as Ratio of ATE Repair Costs to Infrared Imaging Test Equipment Repair Costs Changes

Table 3-3 provides the reader with a quick reference for converting the ratio (of ATE repair costs to infrared imaging test equipment repair costs) into dollars for the cost of repair using infrared imaging test equipment (Alternative 2). The LCC savings is stable within the 95% confidence interval due to the small percentage of single-layer PCBs (15%) repaired by the F-16 depot PCB repair shop. As the ratio increases, and the cost of using infrared imaging test equipment becomes less and less, at its limit, a maximum savings of $1.3 million is that most that could be achieved.

Table 3-3. Values of Infrared Imaging PCB Repair Costs for Figure 3-3

Ratio of ATE Repair Costs to Infrared Imaging Test Equipment Repair Costs	Value of Infrared Imaging Test Equipment PCB Repair Cost
1	$951
2	$475
3	$317
4	$238
5	$190
6	$159
7	$136
8	$119

Figure 3-4 demonstrates how the total number of PCBs repaired by the F-16 PCB repair shop impacts the LCC of Alternative 1 and Alternative 2. When the number of years and cost savings are held constant, the LCC of Alternative 1 and Alternative 2 remain close together with a slight divergence as the number of PCBs increase to 600. This study uses the current number of PCBs (372) repaired by the F-16 repair shop for a

$1.1 million savings. If the total number of PCBs repaired dropped to 200, the LCC savings of Alternative 2 would be $.66 million. If the total number of PCBs repaired increased to 600, the LCC savings of Alternative 2 would be $1.62 million.

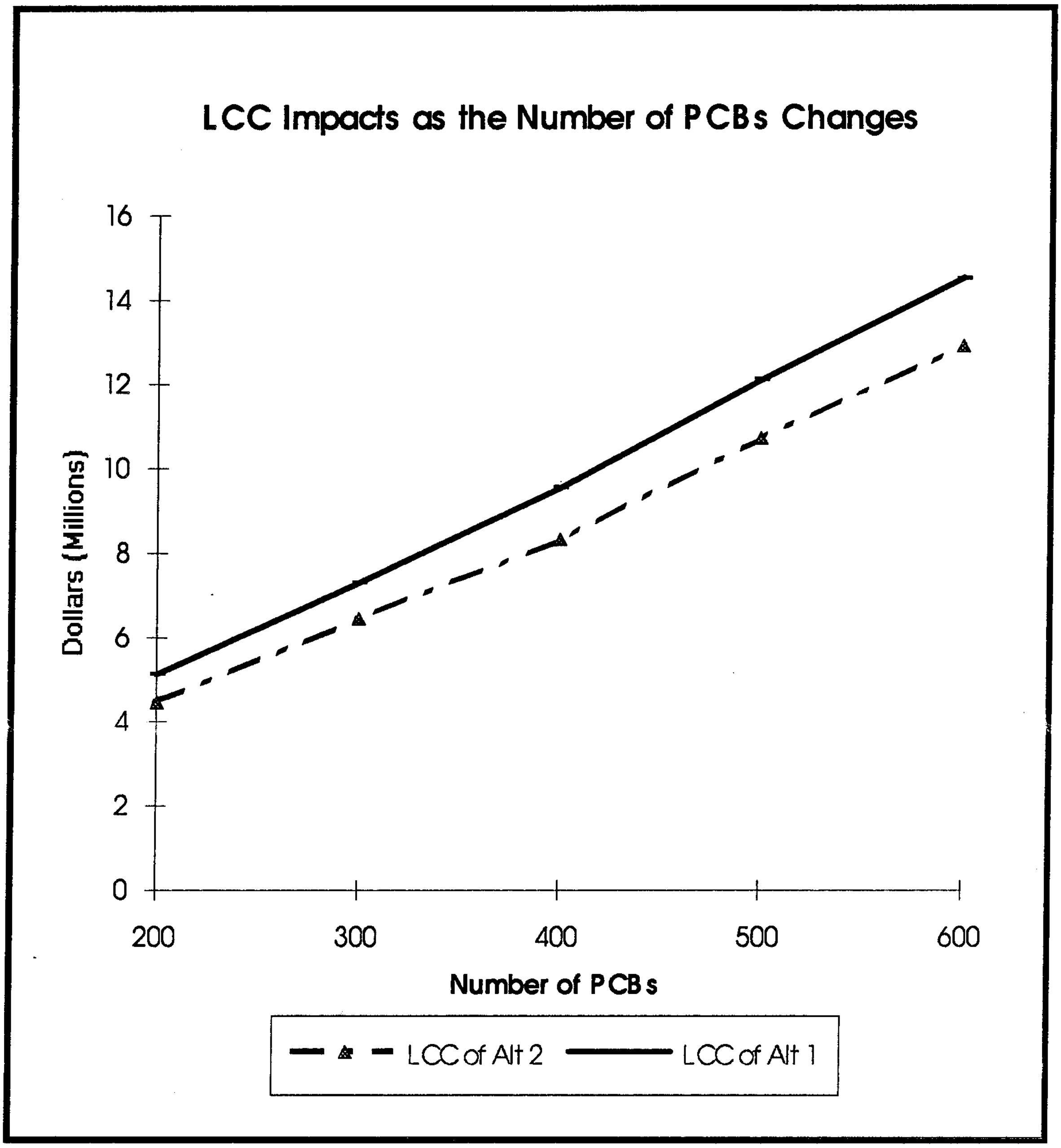

Figure 3-4. LCC Impacts as the Number of PCBs Changes

Figure 3-5 shows the LCC impact on Alternative 1 and Alternative 2 as the number of years change. The current projection for the Ogden ALC F-16 depot PCB repair shop is to support the F-16 for 25 years (until the year 2020) for a LCC savings of $1.1 million. When the repair costs and the number of PCBs are held constant, the LCC of Alternative 1 and Alternative 2 remain close together with divergence as the number of years increase. If the number of years were reduced to five years, the LCC saving of Alternative 2 would only be $160 thousand. This information demonstrates how important the number of years are to the LCC savings of Alternative 2.

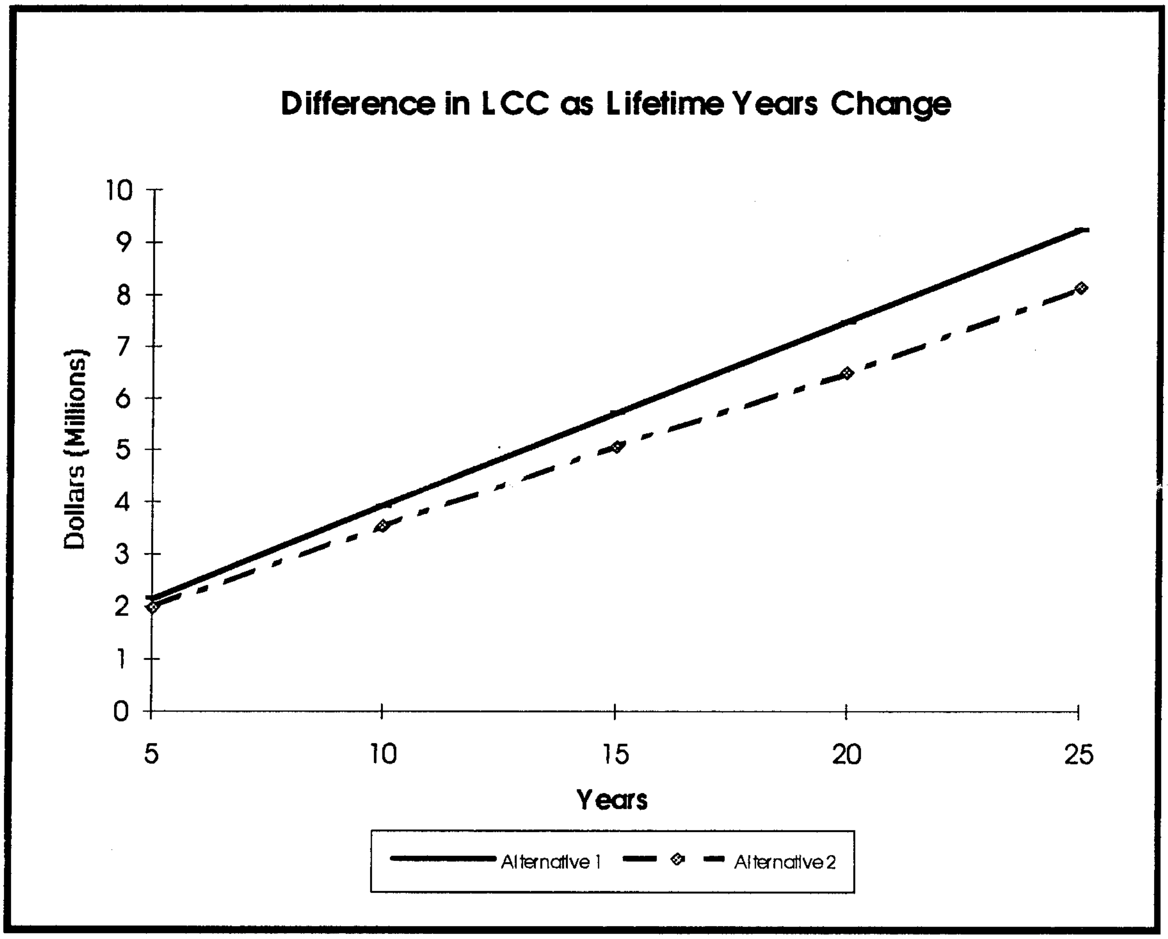

Figure 3-5. Difference in LCC as Lifetime Years Change

IV. Conclusions and Recommendations

Overview

This chapter presents the major conclusions reached from the research done to determine the life cycle costs of the current F-16 automatic test equipment (ATE) (Alternative 1), and the F-16 ATE augmented with the infrared imaging test equipment (Alternative 2). Finally, this chapter presents some recommendations for further research.

Conclusions

The results of the research into automatic test equipment (ATE) and infrared imaging test equipment indicate that infrared imaging is a proven and feasible technology for testing and fault isolating printed circuit boards (PCBs). Although infrared imaging is not suitable as the sole means for testing and fault isolating multi-layer PCBs with more than three layers, it is suitable as the sole means of testing and fault isolating PCBs composed of a single card with one or two layers. For single card PCBs, the fault isolation and repair process time can be reduced from approximately eleven hours using ATE to approximately 1.8 hours using infrared imaging test equipment.

The results of the research and the CASA model life cycle cost analysis indicate that Ogden Air Logistics Center (ALC) could realize about a $1 million savings over the next twenty-five years for F-16 PCB testing and repair by augmenting the current F-16 ATE with infrared imaging test equipment. Even if the number of different types of F-16 PCBs that can be tested using the infrared imaging test equipment falls from 56 (15% of 372) to 19 (5% of 372), there would still be a savings of $485 thousand (1994 dollars) over the next twenty-five years. If the current number of single card F-16 PCBs repaired by Ogden ALC remains at 56 (15% of 372), Ogden ALC would reach a break-even point for the initial investment in the infrared imaging test equipment within three years from the time of purchase. The PCB repair cost ratio sensitivity analysis indicates that the sampling of the cost data has little impact on the difference in Alternative 2's LCC when a 95% confidence interval is used. Significant LCC impacts between Alternative 1 and Alternative 2 were shown when the number of PCBs repaired, the life span, or the percentage of single card PCBs changes. If future Air Force projections to the number of PCBs repaired, the life span, or the percentage of single cared PCB have potential changes, the decision maker can view the impact of those changes to the total LCC predicted in this study.

Infrared imaging test equipment can provide a significant cost savings over ATE for the Air Force. This has an even greater significance in light of the fact that virtually every weapon system in the Air Force uses PCBs. Case by case evaluations would need to be conducted throughout the Air Force to determine the potential LCC savings for any given weapon system. Weapon systems with a large percentage of singe-layer PCBs (greater than 30%) or a long support projection (over 15 years), deserve a close inspection by the Air Force.

Recommendations for Further Research

The research of this thesis indicates that augmenting current automatic test equipment (ATE) with infrared imaging test equipment can provide significant savings to organizations that test and repair printed circuit boards (PCBs). This is especially true if a significant portion of the PCBs tested and repaired are single card PCBs. What has not been addressed in this thesis is the current trend of PCBs in regards to the number of cards and layers each PCB has. If, for example, a weapon system in the future will be mainly using multi-layer PCBs with three or more layers, infrared imaging test equipment as it exists today may not be a prudent way to test and fault isolate that weapons system's

PCBs. If, on the other hand, the trend in PCB layers is toward more single card (single and double layer) PCBs, infrared imaging test equipment could provide potential costs savings over traditional ATE for those weapon systems which use the single card PCBs.

Irregardless of the trend in PCBs toward more or less cards and layers, there are also existing weapon systems, for instance the F-16, that are projected to be in service a number of years that could possibly realize cost savings by augmenting their current ATE with infrared imaging test equipment. The amount of savings for each weapons system would depend on the remaining expected life of the weapons system and the number of single card (single or double layer) PCBs contained in the weapons system.

Further research should look at determining if the trend in PCBs is toward multi-layer boards with three or more layers or toward single card boards with single or double layers. Additionally, research should be conducted to determine what other weapons systems currently in the Air Force inventory and weapon systems in the inventories of the other services contain a significant number of single card PCBs. Those weapons systems with even a modest amount of single card PCBs could possibly derive some economic benefit by using infrared imaging test equipment for PCB fault isolation and repair.

The results of theses two specific areas of research could provide the Air Force and the other services with valuable information in determining if infrared imaging for PCB fault isolation and repair is a technology that can save the military money on a larger scale. If such large-scale savings are possible, the military might implement this technology for fault isolation and repair of PCBs on current and future weapons systems.

An aspect of infrared imaging test equipment that was not fully explored in this thesis due to the limitation of available data was the potential savings that could be realized due to improved reliability of PCBs tested by infrared imaging test equipment. Because infrared imaging test equipment can detect intermittent and impending failures in a PCB, the overall reliability of a group of PCBs, for example the spares stock, should increase. The current database that tracks reliability and maintainability (R&M)

information for the F-16 is known as the Tactical Interim CAMS (Core Automated Maintenance System) and Remis Reporting System (TICRRS). According to Mr. Bob Peck, a logistics analyst at the Systems Engineering and Management Company, TICRRS currently only tracks information at the line replaceable unit (LRU). However, TICCRS is starting to collect data at the shop replaceable unit (SRU) level (16). Because PCBs are considered SRUs, the TICCRS database will eventually collect data on the F-16's PCBs. If the F-16 depot PCB repair shop decides to augment their ATE with infrared imaging test equipment, and if the TICCRS database begins to collect data on the F-16 PCBs, the TICRRS database would be useful in future research in substantiating the claim that by using infrared imaging test equipment the reliability of the PCBs increase.

Finally, infrared imaging is but one of several photonic techniques that are being developed. Research into other photonic techniques such as ultrasound, laser, ultraviolet fluorescence and x-ray should be conducted to determine the current state of the art of each of these techniques, and the potential life cycle cost savings that may be realized by employing these techniques to test and repair PCBs.

Appendix A

Cost Analysis and Strategy Assessment (CASA) Model Data

Cost Analysis and Strategy Assessment (CASA) Model -- Version 3.00

==

Data File Used: C:\CASA30\ATE2.L30

Automatic Test Equipment 10/26/94

RDT&E COSTS

TOTAL RDT&E COST	0

ACQUISITION COSTS

TOTAL ACQUISITION COST	0

OPERATION AND SUPPORT COSTS

TOTAL O & S COST	1,684,800	0	7,568,692	9,253,492

TOTAL LIFE CYCLE COST FOR 312 MONTHS........				9,253,492
				==========

Cost Analysis and Strategy Assessment (CASA) Model -- Version 3.00

Data File Used: C:\CASA30\ATE21.L30

Automatic/Infrared Imaging Equipment 10/26/94

RDT&E COSTS

TOTAL RDT&E COST				0

ACQUISITION COSTS

TOTAL ACQUISITION COST				128,000

OPERATION AND SUPPORT COSTS

TOTAL O & S COST	1,684,800	0	6,334,817	8,019,617
TOTAL LIFE CYCLE COST FOR 312 MONTHS........				8,147,617

BIBLIOGRAPHY

1. Adams, John A. "Beyond 2000 - Imaging for Automated Production Test of PCB Assemblies," 1993 IEEE International Conference on Acoustics, Speech, and Signal Processing, 1: I-48 - I-50. Piscataway NJ: IEEE Service Center, 1993.

2. Allred, Lloyd G. Neural Radiant Energy Detection System: USAF PRAM Program Final Report, 00-253/01591-01. OO-ALC/TISAA, Hill AFB UT, May 1993.

3. Chandler, Thomas L., and Cynthia A. Fredrickson. "Infrared Automatic Mass Screening (IRAMS): An ATE Solution," IEEE AUTOTESTCON '88: 55-57, Piscataway NJ: IEEE Service Center, 1988.

4. Clark, J., G. Georgi, and D. Van Weerthuizen. Digital Printed Circuit Board Tester Requirements for AF Electronic Systems: Final Technical Report, 12 June 1974 - 15 August 1975. Contract F30607-74-C-0237. Fullerton CA: Hughes Aircraft Company Field Service and Support Division, April 1976 (AD-B011608).

5. Dean, H. F., and K. F. Harper. Reliability Screening and Step-Stress Testing of Digital-Type Microcircuits: Research Report, NELC-1512. Naval Electronics Lab Center for Command Control and Communications, San Diego CA, September 1967 (AD-662196).

6. Elmore, Lt Col Travis, F-16 Program Office. Interview. Aeronautical Systems Center, Wright-Patterson AFB OH, 17 July 1994.

7. Gill, Leroy. Life Cycle Cost and Reliability, AMGT 559 Course Handout. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 1994.

8. Goide, Dale, F-16 Repair Shop Supervisor. Telephone Interview. Ogden Air Logistics Center, Hill AFB UT, 7 June 1994.

9. Herman, Ruth A. Aspects of Using Infrared for Electronic Equipment Diagnosis, AFAPL-CONF-67-7, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, November 1966 (AD-642428).

10. Herman, Ruth A. Infrared Data Analysis for Diagnosis, Isolation, and Prediction of Electronic Equipment Malfunctions: Technical Report, AFAPL-TR-69-59. Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, August 1969 (AD-863793).

11. Jensen, Dave, F-16 PCB Repair Shop Program Manager. Telephone Interview. Ogden Air Logistics Center, Hill AFB UT, 9 June 1994.

12. McIntyre J, C. Portz, and J. Coates. The Hidden Costs of Automatic Test Equipment (ATE), AFLMC-LM8709551. Logistics Management Center, Gunter AFS AL, July 1988 (AD-B124489).

13. Moy, Richard Q., Raymond Vargas, and Charles Eubanks. "Predicting Electronic Component Lifetime Using Thermography," Thermosense XIII, Proceedings SPIE 1467: Bellingham WA: SPIE - The International Society for Optical Engineering, 1991.

14. Nye, Curt, DL41 Data Base Manager. Telephone Interview. Ogden Air Logistics Center, Hill AFB UT, 7 June 1994.

15. Office of Management and Budget. "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs," OMB Circular A-94, 29 October 1992.

16. Peck, Charles R., Logistics Analyst. Telephone Interview. Systems Engineering and Management Company, Beaver Creek OH, 14 November 1994.

17. Poeth, Dean F., and Charles Bakis. "Options in Nondestructive Testing of Components and PCB's," Contract and Captive Electronic Manufacturing and Printed Circuit Production, 36: 20-32, Libertyville IL, Lake Publishing Corporation, March 1990.

18. Productivity, Reliability, Availability, and Maintainability Program (PRAM), United States Air Force Fact Sheet.

19. Radecki, Mike, Electrical Engineer. Telephone Interview. Aerospace Guidance and Metrology Center, Newark AFB OH, 29 September 1994.

20. Ross, Douglas A. Optoelectronic Devices and Optical Imaging Techniques, Macmillan Press Ltd., London UK, 1979.

21. Samardar, M. Fault Diagnostic Techniques Analysis: Final Report. Contract F33615-89-C-5708. WL/MTEC, Wright-Patterson AFB OH, July 1991 (AD-B157 564).

22. Seldon, Robert M. Life Cycle Costing: A Better Method of Government Procurement Boulder CO: Westview Press, 1979.

23. Spence, Hugh F., Daniel P. Burris, Jorge Lopez, and Robert A. Houston. "An Artificial Neural Network Printed Circuit Board Diagnostic System Based on Infrared Energy Emissions," IEEE AUTOTESTCON '91: 41-45, Piscataway NJ: IEEE Service Center, 1991.

24. Stojanoff, H. "Possibilities for the Application of the Infrared Testing Method in Electronics," Feingertatetechnik, 7: 289-291, 1972. Translated from German to English by Leo Kanner Associates for US Army Foreign Science and Technology Center, Charlottesville VA, 1973 (AD-920882).

25. Susskind, Alfred K. Testability and Reliability of LSI: Final Technical Report, 15 September 1978 - 31 July 1980, RADC-TR-80-384. Contract F30602-78-C-0292. Bethlehem PA: Lehigh University, January 1981.

26. The Optical Industry & Systems Directory, Optical Publishing, Pittsfield MA, 1978.

27. Wirick, M.P. Manufacturing Methods and Technology Infrared Testing of Printed Wiring Assemblies and Hybrid Microcircuits: Final Report. MICOM MM&T Contract DAAK40-78-C-0276. Los Angeles CA: Hughes Aircraft Company Support Systems Engineering Development Lab, November 1979 (AD-B086048).

Vita

Captain Kent R. Montgomery was born on 21 July 1961 at Chanute AFB, Rantoul, Illinois. He graduated from Dysart High School in Arizona on 22 May 1980. Captain Montgomery attended the University of Arizona on a four year Air Force Reserve Officer Training Corps scholarship. He graduated from the University of Arizona with a Bachelor of Science degree in Aerospace Engineering and received his commission in the United States Air Force on 20 December 1984.

Captain Montgomery's first assignment was to the 31st Test and Evaluation Squadron (SAC) at Edwards AFB, California. As Chief, B-1B Terrain Following Radar Engineering for the B-1B Combined Test Force, he was responsible for operational testing, analysis and evaluation of the B-1B terrain following radar system.

Prior to entering the Air Force Institute of Technology (AFIT) in 1993, Captain Montgomery was assigned to the B-1B System Program Office at Oklahoma City Air Logistics Center, Tinker AFB, Oklahoma. As the B-1B Test and Evaluation Manager, he was responsible for planning, budgeting, and managing the B-1B flight test program for Air Force Materiel Command for all B-1B modifications and upgrades.

Upon graduation from AFIT, Captain Montgomery will be stationed at Kirtland AFB, New Mexico, assigned to the Phillips Laboratory.

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13. ABSTRACT (*Maximum 200 words*)

This study analyzes two alternatives for printed circuit board (PCB) diagnosis for the F-16 depot PCB repair shop from a life cycle cost (LCC) perspective. Alternative 1 assumes the use of the current F-16 automatic test equipment (ATE) while Alternative 2 augments the current ATE with infrared imaging test equipment. Infrared imaging is a developed technology that is currently available to the Air Force in a commercial-off-the-shelf (COTS) form. Using the Cost Analysis and Strategy Assessment (CASA) Life Cycle Cost (LCC) Model and data from the DL41 database on F-16 PCBs, this study determined that over the current expected life of the F-16, the next twenty-five years, a savings of approximately $1.1 million (1994 dollars) can be realized by augmenting the current F-16 ATE with infrared imaging test equipment. 15% of the F-16 printed circuit boards (PCBs) are single card PCBs which can be tested using infrared imaging test equipment. This study assumes that the total number of PCBs and the percentage of single card PCBs does not change over the F-16's lifetime. Sensitivity analyses are performed varying the percentage of single card PCBs, the total number of PCBs, and the F-16 lifetime to determine the effects these changes might have on the total life cycle cost of implementing Alternative 2.

14. SUBJECT TERMS
Printed Circuit Board (PCB), Automatic Test Equipment (ATE), Infrare Imaging, Life Cycle Costs (LCC), Circuit Board Testing, Circuit Board Repair, Photonics, F-16

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